Astrometric Data Sources for Space Surveillance and Space Control

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1 Introduction

The need for precision in space surveillance and space control continues to grow as both the number of satellites increases and the importance of space debris tracking elevates. Improvements in instrumentation, from detection devices to pointing hardware, is one area where precision is being increased. Once data acquisition is made, reduction software comes into play. Regardless of the precision in that software, *a priori* information, such as stellar positions and magnitudes, can degrade the final results if these data are not maintained at the highest level of precision. Systems should be designed to be flexible; the ability to update such *a priori* information is desirable given that astrometric catalogues and their associated photometry continue to improve in both quality of data and quantity of stars.

Over the past four years, astrometric catalogues have taken substantial leaps forward in both precision and density. This is due in large part to the successful Hipparcos mission. Prior to Hipparcos, astrometric measurements of large quantities of stars were made with ground-based instruments, primarily transit circles for large angle measurements and photographic plates for smaller angle measurements. Hipparcos proved that a satellite, free from the distorting effects of the Earth's atmosphere, could produce astrometry one to two orders of magnitude better than ground-based instruments for tens of thousands of stars. In 1997 the Hipparcos Catalogue was released to the public; it is currently recognized as the international standard (ESA 1997).

The Hipparcos data effectively replaced the FK5 catalogue. Compared with FK5's 4652 stars, Hipparcos's 118,218 stars with superior accuracies gives such a dense reference grid that removing systematic errors in both old and new astrometric catalogues is possible. This has lead to catalogues that extend the Hipparcos system to fainter magnitudes, higher densities, and longer wavelengths.

This paper is a review of the current status of astrometric catalogues and a preview of where astrometry will be in the next few years.

2 Optical Sources

Hipparcos Catalogue

The Hipparcos mission was a European Space Agency satellite designed to observe the positions, motions, and parallaxes of about 100,000 of the brightest stars at the

levels of 2 milliarcseconds (mas), 2 mas/yr, and 2 mas, respectively. Launched in late 1989, it failed to achieve its designed geosynchronous orbit and instead remained in a transfer orbit for its 3-year lifetime. However, even with the orbit problem, the satellite performed as expected and all project goals were met. The satellite ended operation in 1993. Aboard were actually two detector systems: 1) the "main mission detector system" – commonly known as the Hipparcos experiment – is the basis for the Hipparcos Catalogue; and 2) the "star mapper detector system" – commonly known as the Tycho experiment – is the basis for the Tycho-1 and Tycho-2 catalogues.

As stated in this paper's Introduction, the Hipparcos Catalogue is the current standard in the optical regime. It should be the first choice of astrometric data when its magnitude range and spatial density is adequate for the task being performed. Hipparcos contains 118,218 stars for an average density of just under 3 stars per square degree. It is complete to visual magnitude 7.3. The astrometric accuracy is magnitude-dependent; brighter stars are good to ≈ 1 mas in position at mean epoch and about 1 mas/yr for proper motion. The faintest stars are about three times worse.

The Hipparcos Catalogue also contains broad-band "white-light" photometry from the main mission mapper as well as medium-band blue and visual photometry from the Tycho experiment. Photometric accuracy is estimated to be a few millimagnitudes for the brightest stars in the broad band, and better than 0.1 magnitudes in the narrow band. Each star was observed at about 110 different epochs, so there is much information regarding variability.

Out of the 118,218 stars, 17,917 are flagged as being in multiple systems or so-called *problem stars*. These are indicated by a C, G, V, O, or X in field 59 of the catalogue. The astrometry from these stars has been shown to be suspect in terms of quoted precision (Urban et al. 2000). Also of note, multiple stars with orbits of comparable duration as the satellite mission, that is from about 2 to 20 years, may have their proper motions quite wrong. For these reason, the International Astronomical Union has adopted a resolution excluding these flagged stars from representing the International Celestial Reference System. It is wise that, if given the option, those working in space control and surveillance use these stars with caution, especially when projecting them several years from the mean catalogue epoch of 1991.25. Details on the Hipparcos mission can be found on the website "http://astro.estec.esa.nl/SA-general/Projects/Hipparcos/hipparcos.html".

Tycho-2 Catalogue

For stars not in Hipparcos, the next source of astrometric and photometric data should be the Tycho-2 Catalogue (Høg et al. 2000). This replaces the ACT Reference Catalogue (Urban et al. 1998), the Tycho Reference Catalogue (Høg et al.

1998) the Tycho-1 Catalogue (ESA 1997), the ACRS (Corbin & Urban 1991), and the PPM (Röser & Bastian 1991).

Tycho-2 is also based on data gathered by the Hipparcos satellite, however not by the main mission detector but by the detector system known as the star mapper. This detector system gave lower astrometric precision than did the main mapper, but the number of stars observed is dramatically more. Compared with the 118,218 stars observed with the main mapper, the 2.5 million stars observed with the Tycho detector gives an increase in spatial density of 20-fold. Tycho-2 is thought to be 99% complete down to V=11.0, and 90% complete at V=11.5. There are stars as faint as V=14.0, but any star fainter than about V=12.0 is likely to be missing.

The lower precision of the Tycho mapper means that the proper motions – if restricted only to those data from the mapper – would be of extremely low quality. Indeed, this was the case for the Tycho-1 Catalogue, with proper motion errors of about 25 mas/yr for its one million stars. However, when the observed positions are combined with older catalogue data, the proper motions can be improved by a factor of ten. The ACT was this type of catalogue, that is a combination of the Tycho-1 positions with that of an older photographic survey (the Astrographic Catalogue). In 1998, the Copenhagen University Observatory re-analyzed the Tycho data and realized that they could provide positions for 2.5 million stars instead of the 1.0 million in Tycho-1. The U.S. Naval Observatory teamed up with them to provide proper motions for these stars, but instead of using one, large, photographic survey to provide proper motions, about 140 individual astrometric catalogues were used. The Tycho-2 Catalogue, as the project became known, was released in February 2000.

There is a fair range in precision of the Tycho-2 data. In general, positional accuracies at observed epoch are better than 20 mas for the stars brighter than V=10.0, but then degrade to 100 mas at V=12.0. This magnitude-dependent degradation is less in the proper motions; the average errors are between 1 and 3 mas/yr over the entire magnitude range. More information is available at the website "http://www.astro.ku.dk/~erik/Tycho-2/".

These two catalogues, Hipparcos and Tycho-2, are currently the standard in astrometry. There is nothing comparable in whole-sky coverage containing positions, motions, and photometry. It is recognized, however, that these two catalogues do not satisfy all needs. Many satellites are fainter than the Tycho-2 magnitude limit, thus making photometric observations – such as those that indicate satellite tumbling or slewing – difficult to calibrate. As one tries to identify and characterize space debris of smaller cross-sections, these two catalogues quickly become inadequate. There are additional sources of astrometry and photometry that can be used when the need to move to fainter magnitudes and higher spatial densities is required.

UCAC

The USNO CCD Astrograph Catalogue project, UCAC, is designed to observe stars between about V=7.5 and 16.0 over the entire sky. Observing began in January 1998 at Cerro Tololo, Chile, and continues there today. It is planned that the telescope will be moved to Flagstaff, Arizona in mid-2001, where it will complete the Northern Hemisphere.

In early 2000, it was decided that a preliminary catalogue covering most of the Southern Hemisphere would be useful for many applications. Although termed "preliminary", that catalogue – called UCAC1 – is the most precise source of astrometry at current epoch for most of its non-Hipparcos stars (Zacharias et al. 2000). The UCAC1 contains over 27 million stars for an average density of over 1700 stars per square degree. Positional accuracies at observed epoch range from about 20 mas for stars brighter than V=14 to about 70 mas for stars at 16.0 and fainter. The proper motion errors are very magnitude-dependent; stars brighter than about V=12.5 have errors in the 1 to 3 mas/yr range, and fainter stars have errors that reach upward to 12 mas/yr.

As stated above, the UCAC is an ongoing project. It is expected that observations will be completed in mid-2003. It will take a few months to make the final reductions and compute proper motions. It is expected that the final catalogue will contain about 60 million stars with positional errors quoted above, but with proper motion errors down below 5 mas/yr for all magnitude ranges covered. Additional information on the UCAC can be found on the project website at "http://ad.usno.navy.mil/ucac/".

USNO A and B

It is recognized that some applications of space surveillance require star densities that even surpass the UCAC data. For these tasks the USNO A 2.0 catalogue should be the current first choice (Monet 1998). The catalogue is based on photographic data measured on the Precision Measuring Machine at Naval Observatory, Flagstaff Station. It contains over 526 million stars down to V≈20 and covers the entire sky. Although it should not be used for stars brighter than about V=12, nothing can compete with the A 2.0 in terms of size or magnitude limit.

For those needing the magnitude limit of the A 2.0 but not requiring the density, there is a subset of nearly 55 million stars available on one CD-ROM. This catalogue, called SA 2.0 (for "selected" A 2.0 stars) is designed to give a uniform density of about 1300 stars per square degree over the celestial sphere.

One recognizable drawback of the A 2.0 is that it does not contain proper motions for its stars. This is currently being addressed, and it is anticipated that by the end

of 2002 the USNO B catalogue will be released. This will be of similar size as the A 2.0 (probably more stars), but will contain proper motions. For additional information on these catalogues, see "http://ftp.nofs.navy.mil/projects/pmm/".

3 Infrared Data

It is recognized that optical data are extremely valuable for many aspects of space control and space surveillance, including improving orbital elements of satellites and identifying satellite launch origins. However, observations in other wavelengths, particularly in the infrared, also require good astrometry in order to extract out desired information. Primarily due to differences in detector technology, precisions in the IR realm are about an order of magnitude lower than that in the optical. There are currently three major sources of astrometry in the IR, two in the near IR and one covering the far IR. None yet covers the entire sky, but this will change in the next year or two.

2MASS

The 2MASS project (Two Micron All Sky Survey) has utilized two specially designed telescopes, one in each hemisphere, to observe the entire sky in three near infrared bands – J (1.25μm), H (1.65μm), and K_s(2.17μm). Currently, two incremental data releases have been made; these cover about 47% of the sky. These include over 162 million point sources and over 500,000 extended sources. It is estimated that the positional accuracies are about 150 mas. Observations have been completed; the final catalogue is scheduled to be released in 2002. Although no proper motions exist, those requiring data in the near-IR bands should first see if the 2MASS data can be utilized. Further descriptions of this project can be found on the 2MASS website at "http://pegasus.phast.umass.edu/2mass.html".

DENIS

DENIS, the Deep Near Infrared Southern sky survey headed by the Paris Observatory, is somewhat similar to 2MASS, however it only covers the Southern Hemisphere. It observed in three bands simultaneously; one band in the optical wavelength, I (0.8 μm), and two at near infrared, J and K_s. The limiting magnitudes are 18.5, 16.5 and 14.0, respectively. Positional accuracies at observed epoch are expected to be better than 1 arcsec. Well over half of the southern sky is completed. For those requiring infrared data in the Southern Hemisphere, DENIS can be utilized. For additional details, see the project website at "http://www-denis.iap.fr/Denis/denis.html".

IRAS

For longer wavelengths, the primary source of data is the IRAS point source catalogue. IRAS, the Infrared Astronomical Satellite, was launched in 1983 and observed in wavelengths of 12, 25, 60, and 100 microns. There were 245,889 point sources observed. Positional accuracies are very poor in comparison to optical astrometry, generally no better than ten arcseconds. However, two products combined the fluxes from IRAS with the astrometric precision of optical catalogues.

CPIRSS and MSX Infrared Astrometric Catalogue

The CPIRSS, Catalogue of Positions of Infrared Stellar Sources, contains 37,700 stars with astrometry from the Hipparcos and Tycho-2 catalogues but fluxes from the IRAS point source catalogue (Hindsley & Harrington 1994). A larger yet similar catalogue, the MSX Infrared Astrometric Catalogue contains 61,242 stars with astrometry from pre-Hipparcos sources. (Note: there is a catalogue of similar name "MSX Point Source Catalogue" that is the product of the MSX mission. This catalogue covers a limited region of the sky, primarily within 5 degrees of the Galactic Equator. The two should not be confused.) The difference in numbers between the CPIRSS and MSX Infrared Astrometric Catalogue is mostly due to the techniques used in confirming identifications between IRAS and the optical catalogues. Either can be utilized when mid and far IR astrometric data are desired.

4 Summary

There are a wide variety of other astrometric sources, too numerous to review here. Many deal with special stars, such as those in multiple systems or with defined orbits. Others cover very restricted regions of the sky, such as the MSX Point Source Catalogue. Many could prove useful under some circumstances.

Tables 1 and 2 summarize this paper. The number of stars/deg^2 is purely an average; regions in each catalogue deviate from these values. The magnitude ranges listed here may not be the extremes in each catalogue, but the range that one is likely to find sufficient coverage.

This review summarizes the sources of astrometric data that those working in space surveillance and space control are likely to find the most useful. With few caveats, if needing optical data one should first utilize the Hipparcos Catalogue, then Tycho-2, then UCAC1, and finally USNO A 2.0. In the near infrared regime, the 2MASS data look likely to become the standard, followed close behind with DENIS. For longer wavelengths, the old IRAS information, especially in the form of the CPIRSS and MSX Infrared Astrometric Catalogue, is the main source to be used.

Table 1: Primary sources of astrometry in the optical.

Catalogue	Number of stars & (stars/deg^2)	Mag. range	σ_{pos} (mas)	σ_μ (mas/yr)
Hipparcos	118,218 (2.9)	0 - 11.0	1 to 2	1 to 2
Tycho-2	2,539,913 (62)	0 - 12.5	20 - 100	1 to 3
UCAC1	27,758,257 (1700)	7.5 - 16.0	20 - 70	1 to 12
A 2.0	526,230,881 (12000)	10.0 - 20.0	200	NA
SA 2.0	54,787,624 (1300)	10.0 - 20.0	200	NA

Table 2: Primary sources of astrometry in the infrared.

Catalogue	Number of stars & (stars/deg^2)	Bands covered	σ_{pos} (mas)	σ_μ (mas/yr)
2MASS	162,213,354 (4000)	J,H, K_s	150	NA
DENIS	100,000,000 (4800)	I, J,K_s	under 1000	NA
IRAS	245,889 (6)	12,25,60,100 μm	10,000	NA
CPIRSS (IRAS)	37,700 (1)	12,25,60,100 μm	1 to 50	1 to 3
MSX (IRAS)	61,242 (1.5)	12,25,60,100 μm	50 to 250	3 to 5

5 References

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